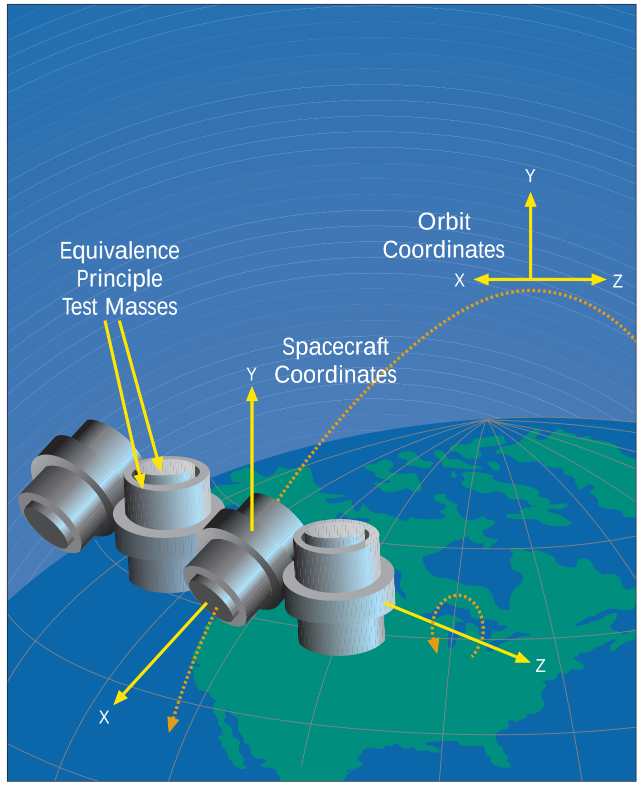
Fundamental Physics



What Is Fundamental Physics?

Fundamental physics is the study of the basic laws that govern the properties of the physical world on all scales, from microscopic to cosmic. The primary focus of the discipline is on acquiring new knowledge about our world and our universe. Our understanding of the laws of the physical world continues to evolve as new information from new experiments becomes available. The discipline of fundamental physics evolves accordingly as technology and techniques improve and broaden the scope of scientific principles that can be experimentally investigated. Scientists study fundamental physics in the microgravity environment because investigations can yield entirely new or substantially improved results when the obscuring effects of Earth's gravity are not present. (See back page for more information on microgravity, or μg.)

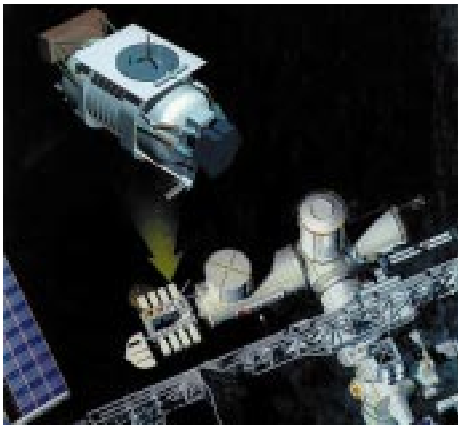
On the cover: The Satellite Test of the Equivalence Principle (STEP), pictured above right, will carry concentric test masses to Earth orbit to test a fundamental assumption underlying Einstein's Theory of General Relativity: that gravitational mass is equivalent to inertial mass. STEP is a 21st-century version of the test that Galileo is said to have performed by dropping a cannonball and a musket ball simultaneously from the top of the Leaning Tower of Pisa to compare their accelerations. During the STEP experiment, four pairs of test masses will be falling around the Earth, and their accelerations will be measured by superconducting quantum interference devices (SQUIDs). The extended time in microgravity, or freefall, and the extreme sensitivity of the instruments will allow the measurements to be a million times more accurate than those made in modern ground-based tests.

The field of fundamental physics has broadened significantly in recent years, expanding to include several new areas of research that can benefit significantly from a microgravity environment. This has prompted the Microgravity Research Division (MRD) to recognize fundamental physics as a thriving and independent discipline within its organization. Until recently, the work of microgravity fundamental physics had been focused primarily on condensed matter physics at extremely low temperatures, with a particular emphasis on investigations of liquid helium. This research was conducted under the auspices of the microgravity fluid physics discipline. Low-temperature and condensed matter physics now make up only one of three major research areas within NASA's microgravity fundamental physics program. The other two areas in which NASA can make a special contribution to fundamental physics are laser cooling and atomic physics, and gravitational and relativistic physics.

The Jet Propulsion Laboratory in Pasadena, California, is NASA's Microgravity Center of Excellence for fundamental physics.

Why Conduct Fundamental Physics Research in Microgravity?

To test some of the universal laws that govern the physical world, it is necessary to go beyond the surface of the Earth. Experiments in fundamental physics related to the investigation of relativity and gravitation are performed in orbit because they need to be conducted at various distances from the Earth to allow the detection of any slight differences in the measurements of Earth's gravitational field or its effects on other forces or phenomena. Microgravity also provides an environment that allows some experiments to be conducted under simpler conditions than are possible on Earth. For example, the force of gravity at the Earth's surface can produce a substantial pressure variation in a fluid experiment sample due to the weight of the sample. The pressure increases with depth and is greatest at the bottom of the sample. This nonuniform pressure in the fluid can cause properties at the bottom of the sample to be different from those at the top. Testing the sample in microgravity eliminates these complications by enabling the sample to be more uniform and more stable.



This illustration shows the Low Temperature Microgravity Physics Facility (LTMPF) planned for the International Space Station. LTMPF will be able to maintain experiment temperatures below 2 Kelvin for up to six months and will have real-time data monitoring and telescience capabilities, allowing scientists to control the experiments from the ground via computer.

Other experiments benefit from the space environment because the microgravity conditions allow longer observation periods than can be achieved through other methods of freefall. In a drop tower, for example, an experiment accelerates very quickly as it drops, experiencing approximately five seconds of microgravity. Such a small window of opportunity limits scientists' ability to gather sufficient data from the experiment. However, an experiment conducted aboard a space shuttle or a space station is in microgravity for extended periods of time, allowing much more data to be gathered.

The microgravity environment is also beneficial because there are fewer potential disturbances to the experiment, such as seismic vibrations, which can affect fundamental physics experiments. Seismic vibrations are caused by the Earth itself and the creatures that inhabit it, including everything from the motion of tides in the oceans to people walking on the laboratory floor. Automobile traffic and other mechanical disturbances, such as heating or plumbing systems, can also cause seismic disturbances. Seismic vibrations are always present on Earth to some degree and can obscure the data of fundamental physics experiments or make it impossible to observe a particular effect that has a measurement magnitude less than the seismic vibration force. Moving an experiment away from the Earth into space is the most efficient way to dramatically reduce these effects and improve the quality of the data collected.

The knowledge gained through fundamental physics research in microgravity offers several potential benefits. One benefit is the creation of highly sophisticated instruments. Since the measurements being made to test fundamental physical laws require great precision, researchers in this field have developed uniquely sensitive instruments. One example is high-resolution thermometers, which have been developed for the study of liquid helium. Through creative use of superconductor technology, these thermometers are able to provide temperature readings to a precision better than a billionth of a degree. Another example of advancement in measurement technology is the ongoing development of highly precise pressure sensors. Both of these devices will likely also be used in microgravity experiments in other disciplines to improve data quality. At major universities, professors and engineers funded by MRD and other NASA divisions are perfecting devices such as gyroscopes and accelerometers, which will help advance MRD's fundamental physics program and the field as a whole.

Other instruments being developed in this field that may have many applications are atomic clocks. These clocks will be more accurate and much smaller than the world's current time standards, which often fill large rooms. Increased accuracy and portability will allow atomic clocks to be used in novel ways to improve navigational technology on the ground, in the air, and in space. Clocks of greater and greater precision will become essential as NASA takes its Human Exploration and Development of Space Enterprise to new levels. Because of the vast distances that must be navigated accurately for deep space exploration or routine space travel, an error of a fraction of a second could translate to veering hundreds of miles off course. More precise clocks will help maintain an accurate course. Atomic clocks can also help aircraft to make more precise landings in situations that require automatic landing systems, such as in inclement weather or when visibility is limited.

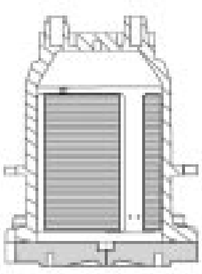
Another benefit of fundamental physics is being revealed as scientific theory evolves. As researchers continue to push the theories of fundamental physics beyond their present limits, they will continue to drive development of new technology and techniques to test their new predictions, and this technology can have application in many other fields. For example, the development of highly accurate experiment sensors that use superconducting technology spawned the magnetic resonance imaging (MRI) technology now commonly used in medical diagnosis. Originally designed for laboratory fundamental physics experiments that used nuclear magnetic resonance (NMR) techniques to study atoms, these sensors were adapted to locate particular types of healthy and diseased tissue in the human body, in many cases eliminating the need for invasive exploratory surgery. Such technological advances are difficult to predict, but they are always possible when scientists push to develop new tools to test and expand our theoretical understanding of the universe.

Fundamental Physics Research Areas

Low-Temperature and Condensed Matter Physics

Condensed matter physics is the study of all physical phenomena related to matter that is in its liquid or solid state. The collections of atoms that make up these condensed states react to variations in pressure, temperature, and other external stimuli. Condensed matter physicists seek to understand the rules that govern these responses so that they can create and improve models that can predict how atoms will react in certain circumstances.

Some condensed matter physicists have particular interest in the properties of states of matter when they are near a critical point, which is a condition of temperature and pressure that is associated with a transition between two phases (i.e., from a liquid to a solid). When approaching a critical point, the properties of the two phases become very similar, and small fluctuations in thermal energy in the material can cause small regions in the sample to pass from one phase to the other. The fluctuations between the two phases tend to dominate the thermodynamic behavior of the material. Therefore, materials near critical points often display many unique properties called critical phenomena. These near-critical-point conditions also cause large numbers of atoms within materials to group together in clusters, the behaviors of which are easier to observe because they are much larger and move more slowly than individual atoms.



The Confined Helium Experiment will consist of studying liquid helium with a specially designed calorimeter (a device used for quantitative thermal measurements) containing over 400 silicon wafers. These wafers will be stacked on top of one another, confining the liquid helium to 50-micron (0.002-inch) gaps between the wafers. Scientists will examine the properties of helium under these confined conditions to distinguish differences from properties of bulk (unconfined) helium.

Special methods have been developed to study critical phenomena in materials that require extremely low temperatures to reach their critical points. A significant proportion of this work has focused on superfluid helium. The notable properties of a superfluid are its ability to conduct heat extremely rapidly without any temperature difference in the superfluid itself and its lack of viscosity (resistance to flow). At atmospheric pressure, helium becomes a liquid at 4.2 Kelvin (-269° Celsius, or 4.2° C above absolute zero) and reaches the superfluid state at 2.17 Kelvin. Liquid and superfluid helium also provide an excellent model system for developing theories about other substances, since interactions between the atoms within a liquid helium sample are limited. By eliminating gravity from the equations describing the motions of the atoms, physicists conducting experiments with helium in microgravity can be much more precise in their calculations of the effects of external stimuli, like heat, on a condensed matter state.

Another unique critical phenomenon occurring at low temperature is superconductivity. When a metal becomes a superconductor, it loses all electrical resistance and has the ability to expel magnetic fields. With superconductivity, electric currents can flow through a metal without any loss of energy, much like superfluid helium can flow without resistance. In a ring of superconducting material, a current (the supercurrent) can thus flow indefinitely, provided the ring is always kept below the superconducting transition temperature. Superconducting technology has been used effectively in experiments for purposes ranging from magnetic shielding to temperature measurement.

Microgravity provides a quiet environment (free of seismic vibrations and relatively free of other disturbances) for working with very sensitive measuring devices that use superconductors. This quiet environment presents fewer obstacles to accurate data collection and can be maintained for a longer period of experimental observation time in space than it can be on Earth. With more precise measuring instruments, increased observation times, and the significant reduction in the force of gravity upon an experiment sample, the “smearing” of data that makes it difficult to distinguish which external stimuli are causing specific effects on a sample is greatly reduced in microgravity.

Laser Cooling and Atomic Physics

Atomic physics is the study of the structure of isolated atoms and their interactions with external stimuli, which include other atoms, surfaces, electromagnetic fields, temperature, pressure, and light. Measurements of these atoms can be remarkably precise if they are well-isolated from external environmental influences, such as collisions with atmospheric gases or with the walls of a container. A common method of isolation is to release the atoms into a high-vacuum chamber. However, the isolation achieved in this method is not perfect. Atoms at room temperature move with a great velocity, which causes them to collide with the chamber walls in a rather short time. This strongly limits the precision of any measurements that can be obtained.

At the atomic level, phenomena in the physical world usually happen at very short length scales and on very fast time scales, making these phenomena difficult to observe. A major difficulty has been overcoming the high-speed movement exhibited by an atom at room temperature. Scientists have searched for methods to slow and trap atoms to make them observable over longer periods.

Laser cooling technology has provided new methods for extending observation times for experiments in atomic physics. Laser cooling uses lasers to slow individual atoms by bombarding them with light of a certain frequency that will exchange momentum with the atoms. This slowing of clouds of atoms allows scientists more time to observe the atoms’ behavior. However, even laser cooling has its limits; when very slow atoms are released into the chamber, they quickly accelerate due to the influence of gravity.

Another strategy for studying atoms involves taking measurements of very cold atoms in an atom trap, which makes use of magnetic or optical forces to loosely contain the atoms and prevent them from falling. When this technique is used in future microgravity experiments, the observation time will be further increased because the cold, slow atoms will not fall out of the range of the observer's view as quickly as they do under the influence of Earth's gravity. The forces used to manipulate the atoms and maintain the trap, however, can interfere with some types of atomic measurements. In microgravity, the forces necessary to manipulate the atoms can be weaker or can be eliminated, and this should lead to even more precise experiments.

The trapping of atoms and laser cooling are also central to improved atomic clocks. When a single laser-cooled atom is trapped, it can be released into the clock mechanism, where it is then stimulated by a second laser to make a transition between two of its internal states. This change of states is usually a change in the motions of electrons within the atom. The electrons shift back and forth, resembling the motion of a pendulum, with a predictable frequency that becomes the time standard for the clock. Atomic clocks will work better in microgravity because the laser-cooled atoms can be manipulated and observed for a significantly longer period of time.

Laser cooling techniques have also been used to cause a cloud of atoms to condense into the Bose-Einstein state, a new state of matter similar to superfluid helium. The Bose-Einstein condensate occurs when atoms at a particular temperature and pressure, on the removal of some energy, fall into lock-step with one another.

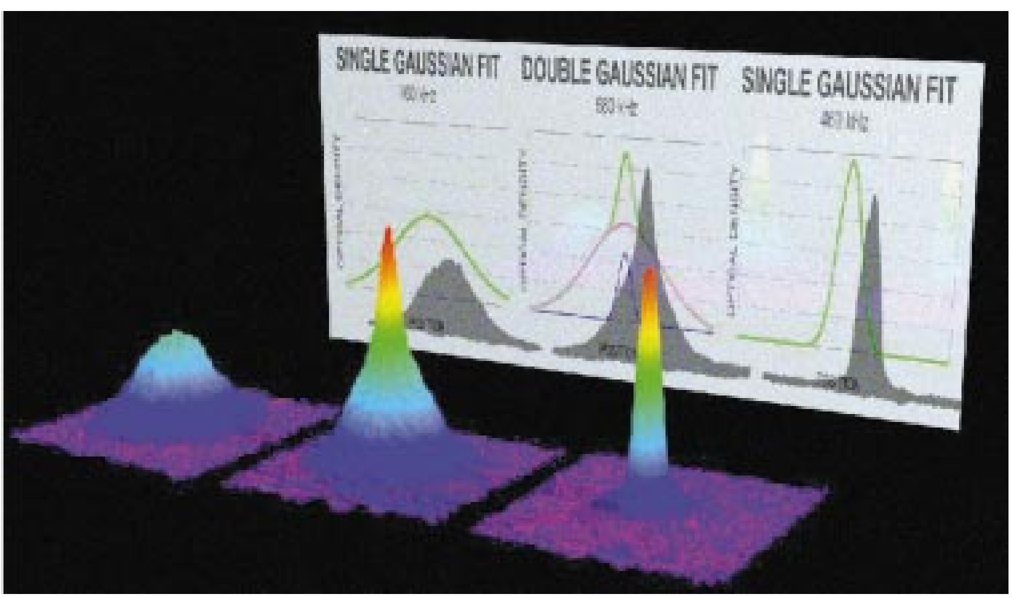
The properties of the Bose-Einstein condensate are still being examined. Studying this phenomenon in microgravity means that larger condensates can be supported in an experiment apparatus for longer periods of time, which in turn should lead to increased understanding of this unique state of matter.

Another use for laser cooling techniques has been found in aiding scientists in the quest to determine an intrinsic electric dipole moment for an atom or elementary particle. The intrinsic electric dipole moment is defined as the difference in the position of the center of the positive charge and the center of the negative charge in a particle or atom. To date, no dipole moments have been observed for the fundamental particles in experiments that have used conventional thermal atomic methods for analysis. According to the most widely accepted model for explaining physics at small length scales, an intrinsic atomic electric dipole moment would only be detectable with techniques that produce results ten orders of magnitude more accurate than those currently used. Competing models that predict larger values for an electric dipole moment could be ruled out with less precise measurements. Scientists expect that laser cooling will provide an order of magnitude improvement in ground-based measurements of this parameter and expect to obtain another order of magnitude improvement when such experiments are taken to microgravity.

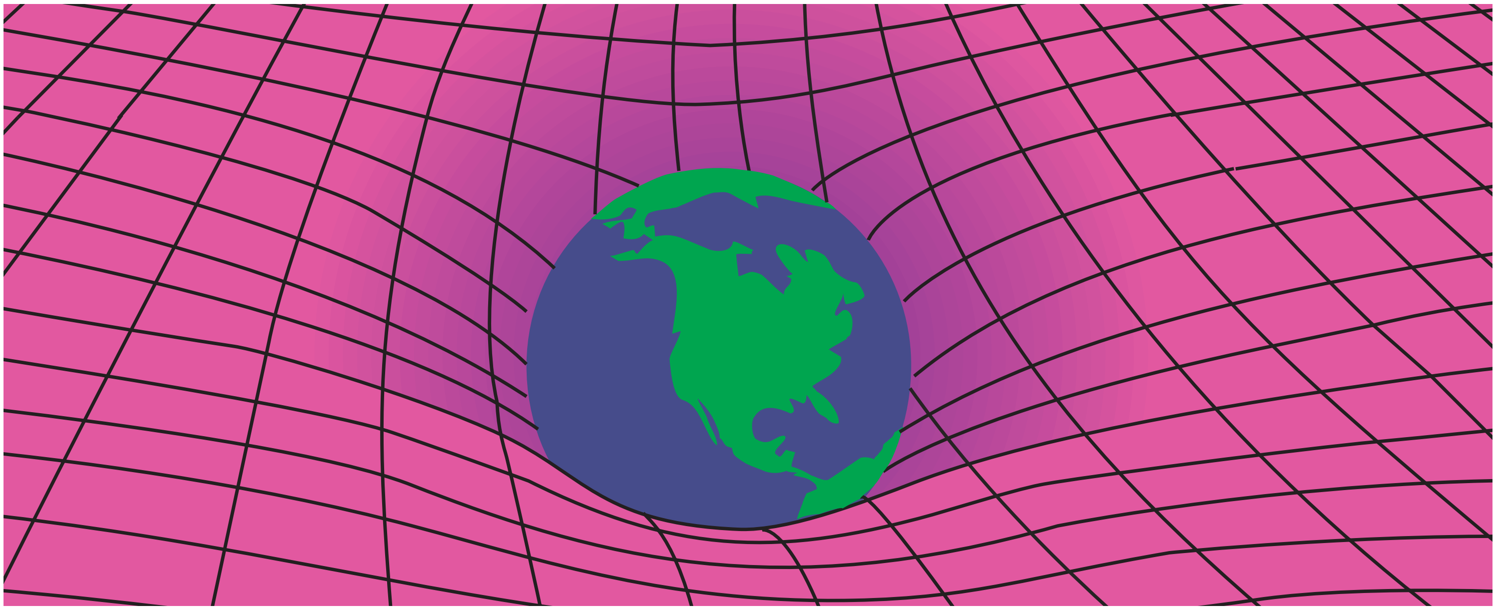
The existence of an electric dipole moment for one of the fundamental particles would constitute a violation of time-reversal symmetry, one of the basic principles of modern physics. According to this principle, any observable event happening as time moves forward (our normal sense of time sequence) would be exactly reversed as time moved backward. Some experiments have provided hints that time-reversal is not a good symmetry because of known instances that some argue are evidence of time-reversal violation, but no universally accepted evidence for such a violation has yet been obtained. The detection of an electric dipole moment at levels greater than those predicted by the standard model of physics would provide unambiguous evidence that the current explanation of phenomena related to the fundamental forces of electromagnetic interaction and weak and strong nuclear interaction is not completely accurate and requires modification.

Gravitational and Relativistic Physics

The research of gravitational and relativistic physics is focused on some of the most fundamental principles of modern physics. High-resolution tests of theories of gravitation can only be conducted in space, where the accuracy of measurements can be increased by several orders of magnitude because the microgravity environment is relatively free of vibrations and eliminates all seismic vibrations that would normally be felt on Earth. Although gravity is the weakest of the four fundamental forces (the others being strong and weak nuclear forces and electromagnetic force), it is the most dominant in the universe because it extends over unlimited distances and encompasses all components of the universe. The twentieth century's premier theorist on gravitation, Albert Einstein, predicted that changes in gravity fields would travel in waves, similar to light and sound waves,



The three images above, produced at millisecond intervals, show a cloud of sodium atoms cooling into the Bose-Einstein condensate, a state in which a majority of the atoms in a substance suddenly rearrange themselves into a compact formation. The atoms can be maintained in the condensate formation for longer observation periods in microgravity than in Earth's gravity, creating better opportunities for scientists to learn more about the properties of the condensate.



This illustration shows how the space-time field is warped by Earth's gravity. The graph-like lines represent the space-time field as a giant mesh sheet. Gravity distorts the space-time field near the planet, causing distances in space to be slightly different than those one might otherwise expect.

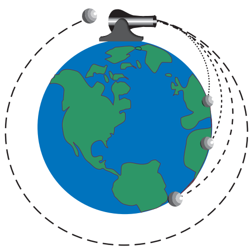
and scientists are attempting to design experiments to detect these weakly interacting waves. Earth-orbiting satellites could be used to measure the Earth's gravitational field with great precision in order to compare these results with predictions of major theories produced by Einstein and other theorists.

Einstein described gravity as a disturbance in the curvature of space and time. This theory is called general relativity. To better understand its effects, one may consider the space-time field as a giant mesh sheet. The gravitational field of each planet, star, or other massive body creates a depression in the mesh, like a marble lying on a taut bed sheet. The result is a slight distortion, or stretching, of the mesh squares near the body. Taking the Earth as one example, this distortion, called the geodetic effect, causes distances in space to be slightly different than those one would expect if the Earth were not there. Einstein also predicted a frame-dragging effect, caused by rotating bodies, that creates another slight disturbance in measurements of space and time. To visualize this effect, imagine that as Earth rotates, it twists the theoretical mesh sheet of space-time and drags it around with the Earth, creating a very slow whirlpool effect. This whirlpool effect causes a disturbance in measurement of space and time, such as when radio transmissions from a satellite passing near a massive body become slightly altered or distorted. These effects are difficult to measure because the instruments must be extremely sensitive and because the measurements must be made in a microgravity environment, which allows an increase in the magnitude of the effects. NASA-funded researchers are designing a drag-free satellite with minimal vibration disturbances to measure the geodetic effect with much greater precision and to calculate the frame-dragging effect for the first time.

Because our concepts of the universe rely fundamentally on theories of general relativity, scientists are driven to put Einstein's theories of gravitation to the most precise tests possible. Modern technology now enables us to make significant leaps in the precision of such tests. The development of drag-free satellite technology will assist the fundamental physics community in its goal of investigating the weak equivalence principle, which asserts that any two objects, regardless of their composition, will experience the same acceleration due to the force of gravity. The most famous test of this principle was performed by Galileo, who allegedly dropped a cannonball and a musket ball from the Leaning Tower of Pisa and found that they hit the ground "within a handsbreadth" of each other. A proposed modern test of this principle would use a drag-free satellite in low Earth orbit to drop four pairs of masses (each pair consisting of concentric hollow cylinders of different materials) at the same time.

This experiment design has two distinct advantages over the original experiment. The first advantage is that the masses can be dropped over a much greater distance, which will allow more time for any variation in relative position of the masses to be observed; instead of the 180-foot height of the Tower of Pisa, the equivalent vertical drop distance of the satellite in orbit is approximately 2,000 kilometers. The other advantage is that during the several months that the satellite will be in orbit, the test of the weak equivalence principle can be repeated thousands of times, accumulating a tremendous amount of data. Other benefits of the experiment design include the reduction of thermal noise (heat fluctuation affecting the accuracy of the data) achieved by conducting the experiment at a very low temperature and the elimination of potential vibration disturbances. This modern test of the weak equivalence principle will enable researchers to measure the difference in the relative position of the objects to within 10^{-15} m (approximately five-billionths of the width of a human hair). Any measured difference in this relative position will necessitate re-evaluation of the current fundamental hypotheses about relativity.

Gravity and Microgravity



In his "thought experiment," Isaac Newton hypothesized that by placing a cannon at the top of a very tall mountain and firing a cannonball at a high enough velocity, the cannonball could be made to orbit the Earth.

Gravity is such an accepted part of our lives that we rarely think about it, even though it affects everything we do. Any time we drop or throw something and watch it fall to the ground, we see gravity in action. Although gravity is a universal force, there are times when it is not desirable to conduct scientific research under its full influence. In these cases, scientists perform their experiments in microgravity — a condition in which the effects of gravity are greatly reduced, sometimes described as "weightlessness." This description brings to mind images of astronauts and objects floating around inside an orbiting spacecraft, seemingly free of Earth's gravitational field, but these images are misleading. The pull of Earth's gravity actually extends far into space. To reach a point where Earth's gravity is reduced to one-millionth of that on Earth's surface, one would have to be 6.37 million kilometers away from Earth (almost 17 times farther away than the Moon). Since spacecraft usually orbit only 200–450 kilometers above Earth's surface, there must be another explanation for the microgravity environment found aboard these vehicles.

Any object in freefall experiences microgravity conditions, which occur when the object falls toward the Earth with an acceleration equal to that due to gravity alone (approximately 9.8 meters per second squared [m/s^2], or 1 g at Earth's surface). Brief periods of microgravity can be achieved on Earth by dropping objects from tall structures. Longer periods are created through the use of airplanes, rockets, and spacecraft. The microgravity environment associated with the space shuttle is a result of the spacecraft being in orbit, which is a state of continuous freefall around the Earth. A circular orbit results when the centripetal acceleration of uniform circular motion ($\mathbf{v}^2/\mathbf{r}$; $\mathbf{v}$ = velocity of the object, $\mathbf{r}$ = distance from the center of the object to the center of the Earth) is the same as that due to gravity alone.

Microgravity Research Facilities

A microgravity environment provides a unique laboratory in which scientists can investigate the three fundamental states of matter: solid, liquid, and gas. Microgravity conditions allow scientists to observe and explore phenomena and processes that are normally masked by the effects of Earth's gravity.

NASA's Microgravity Research Division (MRD) supports both ground-based and flight experiments requiring microgravity conditions of varying duration and quality. These experiments are conducted in the following facilities:

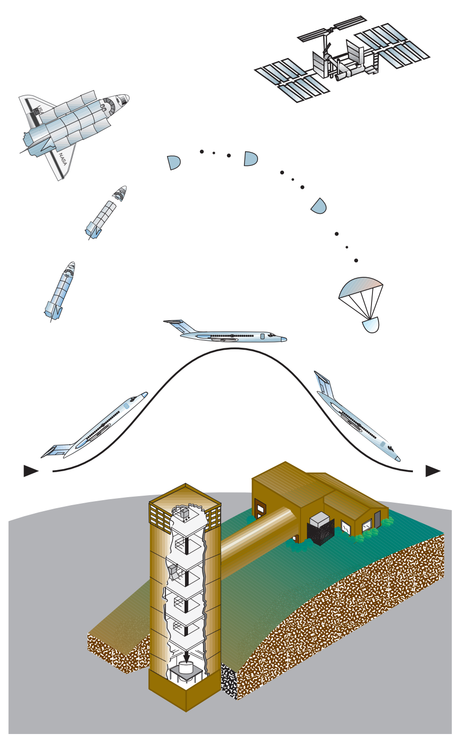
A **drop tower** is a long vertical shaft used for dropping experiment packages, enabling them to achieve microgravity through freefall. Various methods are used to minimize or compensate for air drag on the experiment packages as they fall. Lewis Research Center in Cleveland, Ohio, has two drop facilities (one 24 meters tall and one 132 meters deep) that can accommodate experiments which need only a limited amount of time (2.2 or 5.2 seconds) in microgravity or which are test runs of experiments that will later be performed for longer periods in an aircraft, rocket, or spacecraft.

Reduced-gravity aircraft are flown in parabolic arcs to achieve longer periods of microgravity. The airplane climbs rapidly until its nose is at an approximate 45-degree angle to the horizon. Then the engines are briefly cut back, the airplane slows, and the nose is pitched down to complete the parabola. As the plane traces the parabola, microgravity conditions are created for 20–25 seconds. As many as 40 parabolic trajectories may be performed on a typical flight.

Sounding rockets produce higher-quality microgravity conditions for longer periods of time than airplanes. An experiment is placed in a rocket and launched along a parabolic trajectory. Microgravity conditions are achieved during the several minutes when the experiment is in freefall prior to re-entering Earth's atmosphere.

A **space shuttle** is a reusable launch vehicle that can maintain a consistent orbit and provide up to 17 days of high-quality microgravity conditions. The shuttle, which can accommodate a wide range of experiment apparatus, provides a laboratory environment in which scientists can conduct long-term investigations.

A **space station** is a permanent facility that maintains a low Earth orbit for up to several decades. The facility enables scientists to conduct their experiments in microgravity over a period of several months without having to return the entire laboratory to Earth each time an experiment is completed.



Microgravity Research Division